Recent Results on CP Lifetime Differences of Neutral D Mesons

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Abstract

The mixing parameter y_{CP} for the neutral D system can be obtained by comparing the lifetimes of CP eigenstate decays of the D mesons. Recent results on the lifetime differences from the Belle, CLEO, FOCUS(E831) experiments are summarized in this article. The neutral D decay modes analyzed by the experiments are: The $D^0 \to K^-\pi^+$ mode with the assumption that it is an equal mixture of CP even and odd eigenstates, and the CP even modes $D^0 \to K^-K^+$ and $D^0 \to \pi^-\pi^+$.

1 Introduction

Time dependent interactions of D^0 and $\bar{D}^0$ decays can be coupled by the off-diagonal terms in the Schrödinger equation. If CP is conserved in neutral D decays, the eigenstates will be described as $(D^0 \pm \bar{D}^0)/\sqrt{2}$ with mass and width as $M \pm 1/2\Delta M$, $\Gamma \mp 1/2\Delta\Gamma$. Many calculations conclude that Standard Model contributions to $x(= \Delta M/\Gamma)$ and $y(= \Delta\Gamma/2\Gamma)$ parameters are very small, and new physics effects can manifest themselves as an unexpected large measurement in the x parameter [1]. Experimentally, the mixing parameters x and y are accessible either by searching wrong sign decay of neutral D mesons or by comparing lifetimes of CP eigenstate decay channels. In this article, we summarize recent efforts of various experiments who are exploring the charm mixing sector using the second method. From now on, we assume that the charge conjugate decay modes give the same results as the original decay modes.

For example, if we assume $D^0 \to K^-\pi^+$ decay or its charge conjugate mode are advancing with equal amount of CP even and odd events, the width of the decay channels is described by $\Gamma(K\pi) \approx (\Gamma_1 + \Gamma_2)/2$. Meanwhile, $D^0 \to K^-K^+$

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and $D^0 \to \pi^- \pi^+$ decay modes are CP even and their width is described by Γ_2. Then y_{CP} can be measured as:

$$y_{CP} = \frac{\tau(D \to K\pi)}{\tau(D \to KK)} - 1 = \frac{\tau(D \to K\pi)}{\tau(D \to \pi\pi)} - 1 \tag{1}$$

In the following sessions, the analysis of the FOCUS experiment [2] will be shown as well as the preliminary results from the Belle [3] and the CLEO [4] experiments. Implications of these measurements compared to the result of the wrong sign D^0 decay analysis done by the CLEO experiment [5] will be discussed at the end.

2 The FOCUS CP lifetime analysis

The FOCUS (E831) collaboration consists of 100 physicists from USA, Italy, Brazil, Mexico and Korea. The experiment is a successor to the Fermilab E687 [6] experiment, and its main purpose is to study charm mesons and baryons produced by photon beams of about 180 GeV at a fixed target spectrometer. During 1996-1997 run, the spectrometer collected more than 1 million reconstructed golden mode charm decays, $D \to K\pi$, $D \to K\pi\pi$, and $D \to K\pi\pi\pi$. The FOCUS group used two modes of neutral D decays, $D \to K\pi$ and $D \to KK$, to obtain the y_{CP} parameter.

2.1 The FOCUS spectrometer performance

The target material consists of 4 slabs of Be or BeO, depending on the data run periods. The segmented structure allows 62% of charm particles produced in the target material decaying in air, reducing the absorption correction necessary to the lifetime analysis to a small amount. Two sets of silicon microstrip vertex detectors are built to reconstruct vertices. The components of the first detector set interspace the target slabs, while the second set is located downstream of the target. The combination of the relativistic momentum of charged particles and excellent vertex detector performance produces an extremely good proper time resolution of 30 fs for neutral D mesons, which corresponds to 8% of its lifetime. The good time resolution allows the FOCUS group to use a binned likelihood method free of deconvolution corrections to fit lifetime evolution of charm particles.

The reconstruction algorithm of charm events is optimized to have a flat acceptance over the fit variable, "reduced proper time". The D production and decay vertices are reconstructed by a candidate driven algorithm. A cut is imposed on the amount of detachment (l/σ) between the production and the decay vertices to suppress backgrounds coming from light quark events. Reduced proper time is a variable used by fixed target experiments to measure lifetime of particles, defined as the difference between the proper time and the amount of the detachment cut ($t' = t - N\sigma$).

The FOCUS spectrometer has 3 stations of threshold Cerenkov detectors to identify charged particles. A continuous, likelihood-based identification system is used. This algorithm gives the flexibility useful in assessing systematic errors due to backgrounds.

2.2 Event Selection and Fitting

The event selection is optimized to obtain a sample which has a flat efficiency over the fit variable, t'. First, neutral D meson candidates are required to pass basic section cuts of detachments ($l/\sigma > 5$) and for tracks reconstructed as kaons, the Cerenkov hypothesis to be a kaon should be favored over the hypothesis to be a pion by a factor of 7.39. Second, the candidate is either identified as a decay of D^* (tagged sample) or required to pass more stringent particle identification cuts and kinematic cuts (inclusive sample). As a result, the FOCUS group obtained 119,738 $D \to K\pi$ candidates and 10,331 $D \to KK$ candidates.

Histograms of 20 bins with 200 fs width are used to fit the reduced proper time of the $D \to K\pi$ and $D \to KK$ candidates. In each time bin, the amount of signal is estimated as those of exponential decays adjusted by the absorption/acceptance correction function $f(t')$ obtained from Monte Carlo (MC) simulation. The amount of backgrounds is estimated from the sidebands of D mass lineshape. In case of the $D \to KK$ sample, as shown in Figure 1 (b), a small amount of $D \to K\pi$ reflection background is still lingering in the sideband area. Since the time evolution of the reflection background in the $D \to KK$ sample is governed by the $D \to K\pi$ lifetime, lifetime fitting should be done for both decay samples at the same time. The fit parameters are: $D \to K\pi$ lifetime ($\tau(D \to K\pi)$), the mixing parameter y_{CP}, and normalization parameters of background events for the $D \to K\pi$ sample ($B_{K\pi}$) and for the $D \to KK$ sample (B_{KK}).

2.3 Results and Systematics

Figure 1 (c) shows the reduced proper time evolution of the background subtracted $D \to K\pi$ and $D \to KK$ candidates in the final fit result. The lifetime and the lifetime differences of the neutral D mesons are fitted as follows:

$$y_{CP} = (3.42 \pm 1.39 \pm 0.74)\% \tag{2}$$

$$\tau(D \to K\pi) = 409.2 \pm 1.3 \text{ f}s \tag{3}$$

The systematic error in y_{CP} is obtained by varying selection cuts and by changing lifetime fit options. The systematic error on $\tau(D \to K\pi)$ is not shown, since inputs from other neutral D decay channels, for example, $D \to K\pi\pi\pi$, are needed.

3 The Belle D^0 lifetime study

The Belle collaboration presented a preliminary measurements on lifetimes of D^0, D^+ and D_S mesons at the 4th International Workshop on B physics and CP Violation (BCP4) [3]. The neutral charm mixing study is shown as a part of their lifetime analysis package, based on the data set of 11/fb produced by an asymmetric e$^+e^-$ collider, KEK-B, operating at 12 GeV $\Upsilon(4s)$. The mixing study is performed with two neutral D meson decay modes, $D^0 \to K^-\pi^+$ and $D^0 \to K^-K^+$.

3.1 Event Selection

To suppress the $b\bar{b}$ background smearing into the charm sample, the momentum of D candidates is asked to be more than 2.5 GeV in the $\Upsilon(4s)$ frame. Identification of charged particles is determined by using information from various detectors: a central drift chamber (CDC), a time of flight system (TOF), and an aerosol Cerenkov counter (ACC). K/π separation of up to 3.5 GeV is achieved. To enhance purity of the D sample further, a decay angle cut is applied for each mode. For signal events, the decay angle distribution ($\cos\theta_D$) should be flat. The requirement of the D^* tag is optional. From the selection, the Belle group found $90,601 \pm 387$ $D \to K\pi$ events and $7,451 \pm 118$ $D \to KK$ events.

Proper lifetimes of charm mesons are calculated from the distance between the charm decay vertex and the production vertex ($t = l \cdot m(D)\,/\,p(D) \cdot c$). The decay vertex is reconstructed using all tracks from the charm candidate. The resulting D flight path is extrapolated to the beam interaction region and a production vertex is obtained.

3.2 Lifetime and y_{CP} fit results

An unbinned maximum likelihood fit is used to obtain the charm lifetime and the mixing variable y_{CP}. The likelihood function for each event is described by a sum of following terms: The signal term described by an exponential of lifetime τ_{SIG} convoluted by a resolution function R_{SIG}, a term for background events described by an exponential of lifetime τ_{BG} convoluted by a resolution function R_{BG}, and another term for background events which do not have a lifetime and convoluted by the R_{BG}. For signals (backgrounds), the resolution is 155 (160) fs for 56 (60)% of events and 348 (350) fs for 44 (40)% of events.

A combined lifetime fit using both $D \to K\pi$ and $D \to KK$ distributions is performed and the following lifetime parameters are obtained:

$$y_{CP} = 1.16^{+1.67}_{-1.65}\,\% \tag{4}$$

$$\tau(D \to K\pi) = 414.5 \pm 1.7 \text{ f}s \tag{5}$$

The errors shown above are statistical only. A detailed study on systematic errors is currently going on. The numbers are consistent with separately measured neutral D lifetimes; $\tau(D \to K\pi) = 414.5 \pm 1.7$ fs, $\tau(D \to KK) = 409.8 \pm 6.3$ fs

The Belle measurements on the D^0 lifetime and the mixing parameter y_{CP} are consistent with the ones from other experiments. Figure 2 shows the mass and lifetime distributions used to extract the fit results.

4 The CLEO D^0 lifetime study

At the BCP4 conference, the CLEO collaboration summarized their recent efforts on measurements of $D^0 - \bar{D}^0$ mixing, CP violation in D^0 decays, and D^{*+} width [4]. They showed the preliminary analysis on D^0 lifetime using $D \to K\pi$, $D \to KK$, and $D \to \pi\pi$ decay channels, based on a data set of 9.0/fb produced by a symmetric e$^+e^-$ collider, CESR, operating at 10.6 GeV ($\Upsilon(4s)$).

4.1 Event Selection

The kinematic characteristics of charm particles created in the CLEO detector are similar to those created in the Belle. The D^* tag is required to select neutral D events, exploiting the excellent CLEO resolution on the mass difference between D^* and D^0 ($\sigma_Q = 190 \pm 2KeV$). The CLEO group selected $20,272 \pm 178$ $D \to K\pi$, $2,463 \pm 65$ $D \to KK$ and 930 ± 37 $D \to \pi\pi$ events.

4.2 Lifetime and y_{CP} fit results

The CLEO analysis is also performed using unbinned maximum likelihood fits to proper time distributions of three D^0 decay channel candidates. The fitting method is optimized for finding lifetime differences, not for finding lifetime of neutral D mesons. The resolution function of proper time in the likelihood is described by three Gaussians: One Gaussian for events with correctly measured proper time and two Gaussians for events with mismeasured proper time. For most events, the resolution is about 35% of the neutral D lifetime. The following $\tau(D^0)$ values are obtained for each decay channel: $\tau(D^0 \to K^-\pi^+) = 404.6 \pm 3.6$ fs, $\tau(D^0 \to K^-K^+) = 411 \pm 12$ fs, and $\tau(D^0 \to \pi^-\pi^+) = 401 \pm 17$ fs. The $\tau(D^0)$ values are highly correlated to the D^0 mass constrained in the fit procedure. This fit technique is not used in the dedicated D lifetime analysis published by the CLEO group [8]. Mixing parameter values are calculated as differences in lifetimes among three decay channels:

$$y_{CP}(KK) = (-1.9 \pm 2.9 \pm 1.6)\% \tag{6}$$
$$y_{CP}(\pi\pi) = (0.5 \pm 4.3 \pm 1.8)\% \tag{7}$$

$$y_{CP}(\text{combined}) = (-1.1 \pm 2.5 \pm 1.4)\% \tag{8}$$

This preliminary result is consistent with the measurements from the other experiments. Dominant systematic errors are coming from statistical uncertainty in MC lifetime study (9 fs), background description (8 fs), proper time resolution model (5 fs), and fit procedure (5 fs).

PDG2K	412.6 ± 2.8 [11]	
E791	$413 \pm 3 \pm 4$ [12]	included in PDG2K
CLEO	$408.5 \pm 4.1 \pm 3.5$ [8]	included in PDG2K
FOCUS (E831)	$409.2 \pm 1.3 \pm x^*$ [2]	
SELEX (E781)	$407.9 \pm 6.0 \pm 4.3$ [13]	
Belle preliminary	$414.5 \pm 1.7 \pm x^*$ [3]	
Average of recent values	411.1 ± 1.0 $\chi^2 = 6.7$ for $dof = 4$	

Table 1: The recent results on D^0 lifetime from various experiments are shown in chronological order. The average in the table is obtained from the most recent five measurements. The numbers are consistent between one another. The E791 and CLEO values are already included in the PDG 2K edition [11]. x^* denotes that corresponding systematic errors are not shown by the experiments yet.

5 Conclusion

The most recent five results on D^0 lifetime are shown on Table 5. The measurements obtained by the FOCUS and the Belle experiments from the lifetime difference analysis are comparable to those from the dedicated D^0 lifetime analysis.

Table 5 shows compilation of y_{CP} values obtained by various experiments. The numbers are comparable to one another, producing an average of $(1.8 \pm 1.0)\%$ with $\chi^2/dof = 2.3/3$. On the other hands, the CLEO experiment published an impressive paper on the neutral D mixing parameters, x' and y' by analyzing lifetime evolution of wrong sign decays of neutral D mesons ($D^0 \to K^+\pi^-$) [5]. On the surface, the average y_{CP} value is comparable to the CLEO wrong sign results, $-5.8\% < y' < 1\%$ at $95\% CL$. But one has to be careful when combining y_{CP} and y' together. The y' and y_{CP} parameters are differed by a strong angle $\cos\delta$ originated from final state interactions. The strong angle has been considered to be small, but a recent theoretical paper suggested possibilities of not so small $\cos\delta$ [9]. The results on two y parameters have comparable errors but opposite signs, which prompted interesting discussions and speculations on neutral charm mixing [10]. This situation implies that mixing measurements in charm sector are challenging studies. We are eagerly waiting for up-to-date inputs from B-factories and next generation experiments to further enhance understanding in ever fascinating mixing phenomena.

E791	$(0.8 \pm 2.9 \pm 1.)\%$ [12]
FOCUS (E831)	$(3.42 \pm 1.39 \pm 0.74)\%$ [2]
Belle preliminary	$(1.16^{+1.67}_{-1.65})\%$ [3]
CLEO preliminary	$(-1.1 \pm 2.5 \pm 1.4)\%$ [4]
Average of y_{CP}	$(1.8 \pm 1.0)\%$
	$\chi^2 = 2.3$ for $dof = 3$

Table 2: The recent results on the D^0 lifetime difference y_{CP} obtained by various experiments via $D \to K\pi$, $D \to KK$, and $D \to \pi\pi$ channels are shown in chronological order. The numbers are consistent between one another. One has to be careful if y_{CP} values should be compared with y' parameter measurements.

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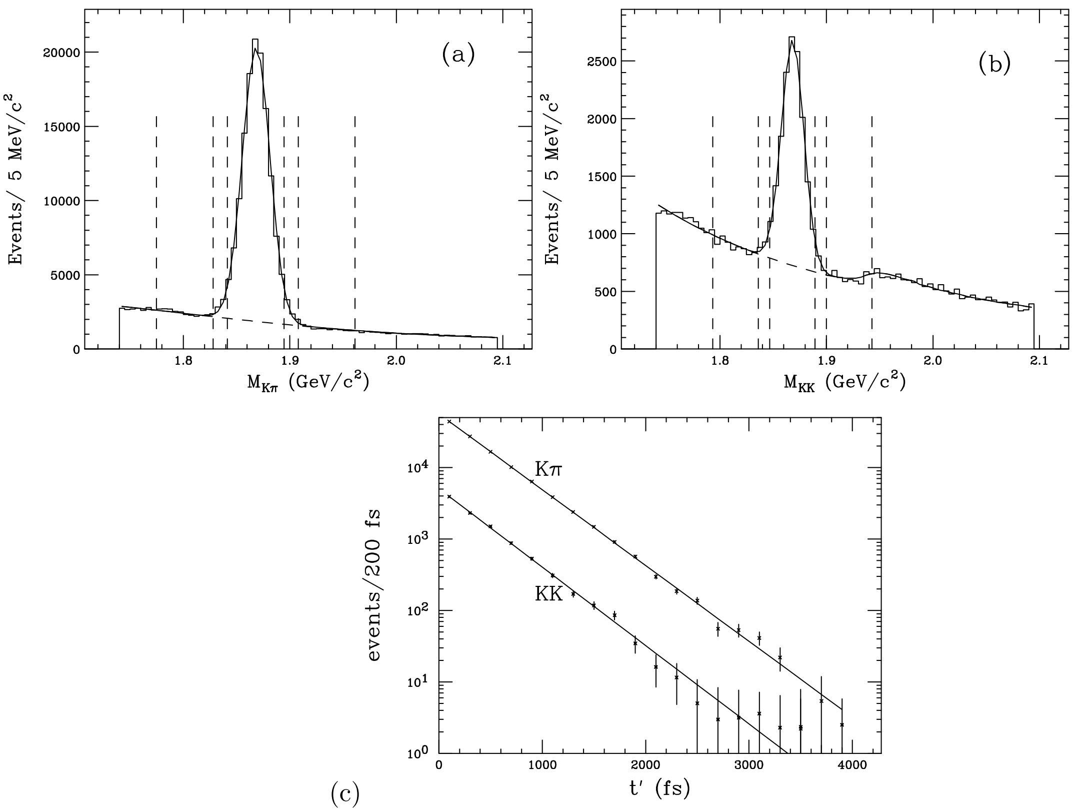

(c)

Figure 1: (a) Reconstructed mass distribution of $D^0 \to K^-\pi^+$ and its conjugate candidates from the FOCUS experiment. The yield is 119 738 $K^-\pi^+$ and $K^+\pi^-$ signal events; (b) That of $D^0 \to K^-K^+$ candidates. The yield is 10 331 K^-K^+ signal events. The vertical and dashed lines indicate the signal and sideband regions used for the lifetime and y_{CP} fits; (c) Signal versus reduced proper time for the $D \to K\pi$ and $D \to KK$ events shown above. Each data point is background subtracted and includes the (very small) Monte Carlo correction; The plots shown here are reprinted from [2].

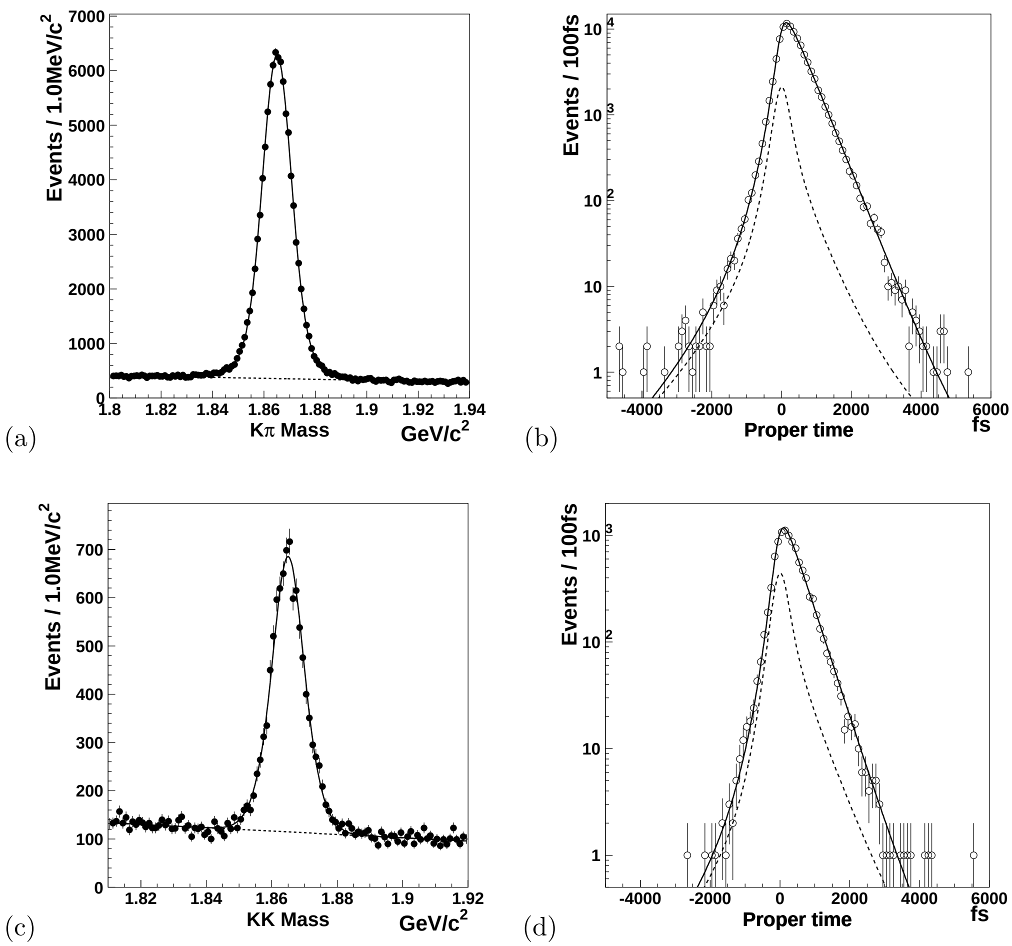

Figure 2: Preliminary results from the Belle experiment on neutral D lifetime differences [3]; (a) Reconstructed mass distribution of $D^0 \to K^-\pi^+$ and its conjugate candidates. The yield is $90,601 \pm 387$ $K^-\pi^+$ and $K^+\pi^-$ signal events; (b) The proper time distribution of the $D \to K\pi$ sample. The dashed line is the estimated background in the sample; (c) Reconstructed mass distribution of $D^0 \to K^-K^+$ candidates. The yield is $7,451 \pm 118$ K^-K^+ signal events; (d) The proper time distribution of the $D \to KK$ sample. The dashed line is the estimated background in the sample.

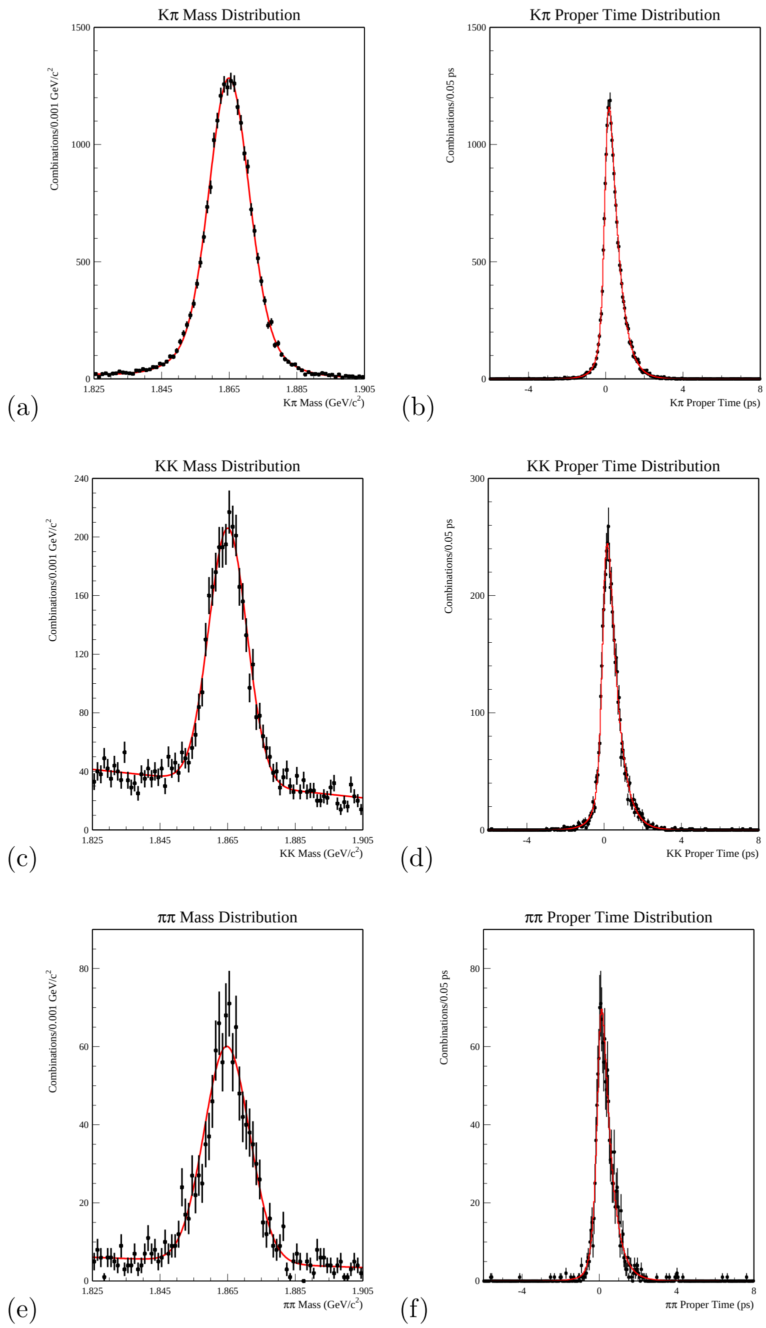

Figure 3: Preliminary results from the CLEO experiment on neutral D lifetime differences [4]; (a) Reconstructed mass distribution of $D^0 \to K^-\pi^+$ and its conjugate candidates. The yield is $20,272 \pm 178\, K^-\pi^+$ and $K^+\pi^-$ signal events; (b) The proper time distribution of the $D \to K\pi$ sample; (c) Reconstructed mass distribution of $D^0 \to K^-K^+$ candidates. The yield is $2,463 \pm 65$ K^-K^+ signal events; (d) The proper time distribution of the $D \to KK$ sample; (e) Reconstructed mass distribution of $D^0 \to \pi^-\pi^+$ candidates. The yield is 930 ± 37 K^-K^+ signal events; (f) The proper time distribution of the $D \to \pi\pi$ sample